Wireless Channel Characterization and System Analysis of Complex Utility Tunnel Environments

Mikel Celaya-Echarri [1], Leyre Azpilicueta [1,*], Peio Lopez-Iturri [2,3], Imanol Picallo [2,3], Erik Aguirre [2], Jose Javier Astrain [4], Jesús Villadangos [4] and Francisco Falcone [2,3]

[1] School of Engineering and Sciences, Tecnologico de Monterrey, Monterrey, 64849, NL, Mexico; mikelcelaya@gmail.com (M. C.-E.); leyre.azpilicueta@tec.mx (L.A.)

[2] Electric, Electronic and Communication Engineering Department, Public University of Navarre, Pamplona, 31006, Navarra, Spain; peio.lopez@unavarra.es (P.L.-I.); imanol.picallo@unavarra.es (I.P.); erik.aguirre@unavarra.es (E. A.); francisco.falcone@unavarra.es (F. F.)

[3] Institute of Smart Cities, Public University of Navarre, Pamplona, 31006, Navarra, Spain; peio.lopez@unavarra.es; francisco.falcone@unavarra.es

[4] Mathematical Engineering and Computer Science Department, Public University of Navarre, Pamplona 31006, Spain; josej.astrain@unavarra.es (J.J.A.); jesusv@unavarra.es (J.V.)

* Correspondence: leyre.azpilicueta@tec.mx; Tel.: +52 81582082; fax: +52 8183597211

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Abstract: The evolution of wireless communications has led to the adoption of a wide range of applications not only for the general public, but also including utilities and administrative authorities. Consequently, the huge growth of new city services requires in some specific cases the construction of underground tunnels in order to reduce visual impact within the city center, as well as enabling maintenance and operation works of utilities. One of the main challenges is that inherently, underground service tunnels lack of coverage from exterior wireless systems, such as mobile networks or municipal WLAN networks, which can be potentially dangerous for maintenance personnel working within the tunnels. In this work, wireless channel characterization for urban tunnel scenarios will be analyzed based on the assessment of LoRaWAN and ZigBee technologies operating at 868 MHz. For that purpose, a real urban utility tunnel has been modeled and simulated by means of an in-house 3D Ray Launching code and compared with experimental measurements, showing good agreement. The singularity and complexity of the limited tunnel dimensions and the inclusion of additional elements such as service trays, user pathways and handrails have been considered. Results provide an adequate radio planning approach for the deployment of wireless systems in urban utility scenarios, with optimal coverage and enhanced quality of service. Besides, in order to have access to the data obtained by the potential WSN deployed within the tunnels, a solution to store such information in a Cloud is included in the study.

Keywords: Wireless Sensor Networks; LoRaWAN; ZigBee; 3D Ray Launching; tunnel environment; Smart Cities

1. Introduction

The evolution of wireless communication has led to their adoption in a wide range of applications, including utilities and administrative authorities. In addition, the growth in population as well as in the services offered in cities has led in some cases to the construction of underground tunnels in order to reduce visual impact within the city center, as well as facilitating maintenance and operation works of utilities. One of the issues that local authorities have considered is the fact that

inherently, underground service tunnels lack of coverage from exterior wireless systems, such as mobile networks or municipal WLAN networks, which can be potentially dangerous for maintenance personnel working within the tunnel. Therefore, wireless coverage should be deployed within the underground installation in order to guarantee real time connectivity.

Radio propagation within the interior of galleries and tunnels has been studied for different wireless systems [1–3], as well as for different tunnel geometries [4]. Other approaches have developed diffraction-based models, such as alternate direction implicit parabolic equation method [5], boundary element method [6], numerical calculation of vector parabolic equation [7] or application of perturbation theory, among others. Another approach is based on the use of deterministic methods, such as ray launching (RL) or ray tracing (RT). One of the main issues is inherent divergence within the ray launching calculation as distance increases between transmit and receive antenna. In this case, solutions in scaled frequency models have been given by reconstructing the initial wave front of the source, achieved by ray density normalization [8]. One of the approaches adopted to perform wireless characterization within tunnels has been the adoption dielectric waveguide models, in which the tunnel is emulated by a waveguide with dielectric walls [9]. These models, however, do not take into account additional complexity, which appear in underground service tunnels, such as ducts, walkways, or distribution trays, among others. Complete modeling can be achieved by employing full wave electromagnetic simulation techniques, such as Finite Difference Time Domain (FDTD) or Frequency Domain Finite Element techniques [10,11]. However, the computational cost can be very high, due to the large size of the tunnel structure as compared to the wavelengths considered in conventional wireless communication systems. Moreover, tunnels analyzed are usually devoted to road traffic or trains, with inherently larger cross-sections and lower structural complexity as compared with utility tunnels, with dense obstacle distribution.

In this paper, an in-house 3D RL code is employed to analyze wireless propagation in urban tunnel scenarios at 868 MHz operation frequency. By adequately modeling the tunnel structure, a precise characterization for the complete extension of the tunnel can be obtained.

The paper is organized as follows: the considered underground scenario to be assessed is described in Section 2. Section 3 presents the radio channel analysis and the required convergence analysis due to the particular characteristics of the scenario. In Section 4, WSN deployment issues are discussed. Finally, discussion and future works are given in Section 5.

2. Scenario under Analysis

In this work, the underground utility tunnels located in the Old Town of Pamplona (Navarre, Spain) have been analyzed. Figure 1a and Figure 1b show the location and a real picture of the considered tunnels. The tunnel under analysis was built in the early 2000s, under some specific streets, with the aim of easing maintenance operations. The tunnel consists of an outer layer of connected cement rings, with the inner part allocating several metallic trays for the corresponding utilities. A metallic hallway has also been installed in order to provide access to maintenance personnel, as can be seen in the figure. Currently, they provide a route for electrical connections, telephone connections, waste disposal and water distribution systems of the neighborhood.

Regarding security, the utility tunnels include common intrusion detection and anti-fire systems, with their corresponding local alarms. But one of the main concerns of Municipal Authorities is the lack of wireless coverage within the tunnels, which initially was planned to be provided by external infrastructures, such as municipal WiFi of Mobile Networks (3G/4G). But in reality, a specific indoor coverage system is required in order to, at least, provide coverage to the maintenance staff that needs to come to the tunnels.
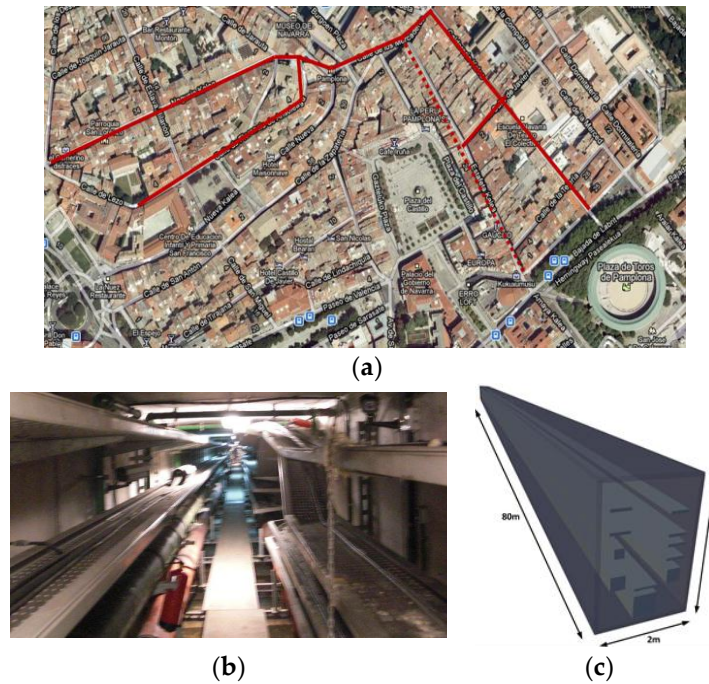
Figure 1. (**a**) Google Earth view of Pamplona, with the utility tunnels marked in red; (**b**) Layout of one of the underground utility tunnels; (**c**) Simulation model created for the 3D RL.

One of the particular aspects of this scenario is the fact that the tunnel is not a conventional tunnel (i.e., free hallway with walls which can be smooth or can present a certain degree of surface roughness and hence, diffuse scattering), due to the fact that there is a set of service trays placed inside the tunnel. This leads to new interactions with the electromagnetic waves launched by the source, with strong multipath component generation given the large ratio between the length of the tunnel in comparison with the width of the tunnels, tray dimension and inter-tray distance. This condition implies for the need of including more precise topological information of the scenario in order to consider the interaction, specifically for launched rays within a ray launching algorithm, as the one employed in this work.

3. Radio Channel Analysis

In order to characterize the radio channel within the proposed utility tunnel, simulations by means of the 3D RL in-house developed code are performed. The algorithm is based on geometrical optics (GO) and geometrical theory of diffraction (GTD). The code has been programmed in Matlab, and an exhaustive description of its operation procedure is presented in [12].

Figure 1c shows the created tunnel scenario. Real material properties have been considered, basically cement walls, aluminum trays and PVC tubes of different dimensions. The dimensions of the tunnel section are the following: width 2 m, height 3 m and section length 80 m. Large scale propagation analysis has been performed by means of the RF power distribution for the whole volume of the scenario. For that purpose, the transmitter antenna has been placed at the beginning of the tunnel model, at a height of 2m (represented by a red triangle in Figure 2). The operation frequency has been set to 868 MHz and the transmitted power to -10 dBm, emulating a ZigBee or LoRaWAN system at this specific frequency. Figure 2 shows the obtained RF power distribution estimations for the XY bi-dimensional plane at a height of 2m (the same height as the transmitter antenna). It can be seen the variability of received power along the distance, showing some spatial points with lower received power in the final part of the tunnel.
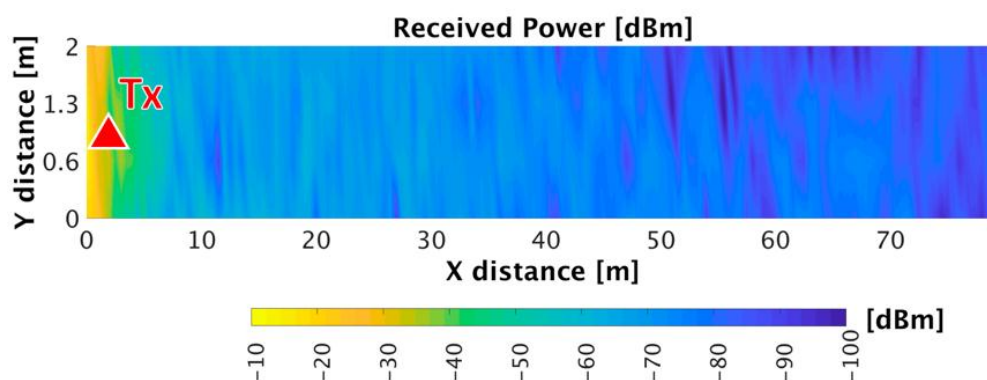
Figure 2. RF power distribution for the XY bi-dimensional plane at 2m height for 868 MHz.

Convergence Analysis of the Scenario

The underground tunnel scenario has distinctive characteristics which convert it in a particular scenario for radio wave propagation purposes. These peculiar characteristics are that it is an area which is considerably long (80 m long in this specific case) and extremely narrow (2 m width). It can be found in the literature [12], the convergence analysis of the in-house RL algorithm to obtain the optimal input parameters for best performance of the algorithm in typical indoor complex scenarios. However, for this specific environment, those parameters are not the optimal because the RL algorithm diverges due to the extremely narrow width of the scenario. The divergence of the algorithm means that there are a lot of cuboids of the scenario that do not have any ray if the same simulation parameters are used for this specific scenario.

Because of that, a specific convergence analysis of the algorithm has been done for this underground tunnel environment in order to characterize 3D RL convergence as a function of multiple parameters, such as cuboid dimensions, angular resolution or maximum number of reflections. Due to the specific characteristics of the utility tunnel environment (i.e., strong reflections due to partial conductor material presence and large obstacle density), the maximum number of reflections and the angular resolution of launching rays have been assessed. Once the simulation results for the different cases have been obtained, radio channel measurements inside the tunnel section have been performed with the aim of validating those simulation results. The measurements have been carried out with the aid of an Agilent CSA N1996A to generate the RF signal and an Agilent FieldFox N9912A portable spectrum analyzer to measure the RF signal power. The transmitter has been connected to a 5dBi monopole antenna, whereas the receiver has been connected to small vertical monopole antenna. The considered frequency of operation has been 868MHz with a transmitted power of −10dBm. The transmitter antenna has been placed at the beginning of the tunnel, located at the center with a height of 2m, whereas the measurement points have been placed in a linear path in front of the transmitter, along the tunnel (2m distance between them). Measurements have been performed with no users crossing the tunnels or other potential time-varying scatterers within the scenario. The results, compared with the different simulation cases, are depicted in Figure 3. Cases 1, 3, 4 and 5 do not have good agreement with measurements after approximately 50 m. This is because Case 3, 4 and 5 consider lower angular resolutions (1 and 0.5 degrees versus 0.2 degrees). In Case 1, the angular resolution is high but the number of reflections is the lowest. On the other hand, Case 2 and Case 6 present a good match with real measurements. Therefore, we can conclude that the 3D RL simulation algorithm has been calibrated to be employed in this particular underground scenario.
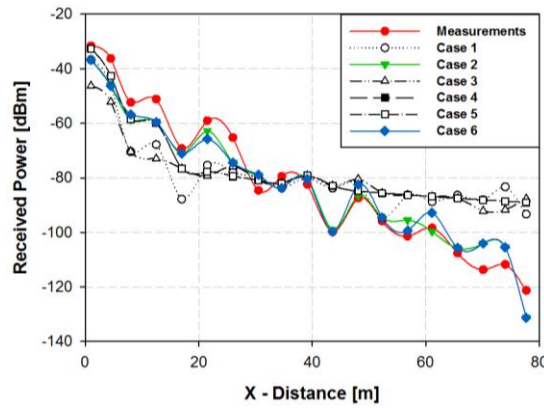
Figure 3. Comparison of different cases of simulation and measurement results for the service tunnel section under analysis.

4. WSN Deployment

The 3D RL simulations showed to be accurate for an optimized radio planning analysis in this complex and particular underground scenario. Based on these preliminary results, the coverage for both Zigbee and LoRaWAN wireless devices can be estimated (i.e., the number of wireless nodes required for the whole tunnel), taking into account that ZigBee and LoRaWAN devices' sensitivity is around -100 dBm and -148 dBm respectively. Besides, the network topology gains a great importance, since the tunnels' particular morphology could limit the use of star topology (the typical one for LoRaWAN).

Regarding the data collected by the WSN, it will be stored, processed and analyzed in a private cloud. For that purpose, we have implemented an Apache CloudStack over hypervisors VMware ESXI managed by a VMware vSphere. The resulting infrastructure allows the agile and easy deployment and management of services. It allows computing orchestration, user and account management and native APIs. Figure 4 (right) depicts the hardware infrastructure where the cloud is implemented, and the interface of the vSphere client (Figure 4, left) where different virtual machines are deployed. The cloud provides data storage, as well as data visualization with the aid of a Grafana tool, and data analytics by means of a BIRT report tool. The resulting computing cloud is easily scalable and allows hot migrations according to the availability of the servers.
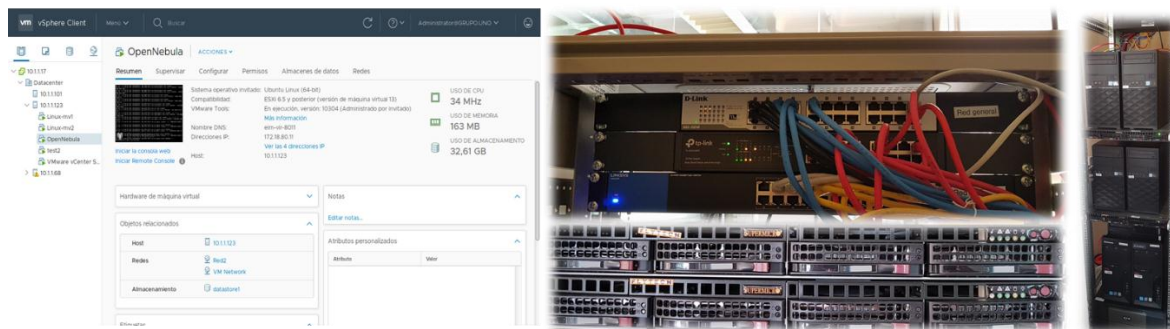

Figure 4. vSphere client (left) and hardware infrastructure (right).

5. Discussion and Future work

In this work, the analysis of wireless system deployment in urban utility tunnels is described. The impact of large obstacle density, given by the inclusion of elements such as service trays or handrails in the case of underground utility tunnels is analyzed by means of in-house 3D Ray Launching code. Complete volumetric analysis is performed in order to consider the location of wireless transceivers and enable them to be embedded within the elements of the tunnels. System

level analysis considering conventional transceiver parameters has been performed, obtaining initial deployment planning results. The proposed methodology enables to consider specific propagation losses in urban utility tunnels, in order to deploy wireless systems with optimal coverage, minimum interference and enhanced quality of service. Future developments require analyzing longer tunnel runs and the impact in wireless channel analysis, in which the high density of scatterers will influence overall channel characterization, in terms of convergence analysis. Moreover, in depth characterization of Wireless sensor configurations are required in order to provide assessment in the election of systems such as ZigBee or LoRaWAN, as a function of topology, maximum transmission rate and receiver sensitivity thresholds.

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